

Modulation transfer function of active pixel focal plane arrays

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ABSTRACT

Modulation Transfer Function (MTF) is an important figure of merit in focal plane array sensors, especially for accurate target positions such as star trackers. In-situ evaluation by MTF in different stages of imager system developments is necessary for an ideal design of different sensors and their signal processing. Understanding the tradeoff between different figures of merit will enable designers to achieve the most efficient design in specific missions. Advanced active pixel test sensors have been designed and fabricated where different pixel shapes were placed. Research on analyzing the MTF for the proper pixel shape is currently in progress for a centroidal configuration of a star. Explicit formulas for the modulation transfer function have been studied for the rectangular shaped pixel array. MTF will give us a more complete understanding of the tradeoffs opposed by the different pixel designs and by the signal processing conditions. In this paper, preliminary results of two different active pixel sensor (APS) focal plane arrays are presented in terms of crosstalk using a laser. MTF measurements of the APS arrays are achieved by applying only a single image. A rising or falling edge rather than the conventional bar target of slit scanning is needed to perform the measurement in each direction for the evaluation of the design efficiency.

Key words: Active pixel sensor, modulation transfer function, focal plane array, sensor responsivity, crosstalk, star trackers.

1. INTRODUCTION

The development of active pixel sensor focal plane arrays with considerable on-chip processing, digitizing, and notably time-delayed integration, imposes new and severe requirements on the instrumentation to establish the modulation transfer function (MTF) of the integrated focal plane array. Is the star tracking sensor¹ system accurate enough to determine the target position? What is the minimum resolvable temperature-difference that can be achieved from an unmanned spacecraft? These are among the most common questions that designers of the imaging systems want to answer. One of the most well-established techniques to dispel any doubt in a single detector imaging sensor array is the measurement of the Modulation Transfer Function (MTF), which is a spatial frequency response of the imaging system. A microelectronic, advanced laser scanner has been used to probe sensor responsivity at room and liquid nitrogen temperatures using a micron-size laser beam that scans in less than a micron step. Recent advancement² of the MTF test methodology for infrared cameras makes the testbed a reachable goal by modifying the existing microelectronic advanced laser scanner (MEALS³) with up-to-date personal computers in hand. The MTF measurement can be achieved by applying a modified, knife-edge technique to the existing MEALS system for the optical and thermal imagers. By utilizing this technique², only a single image containing a rising or falling edge is needed to perform the measurement in each direction rather than the conventional bar target of slit scanning. An estimation of the ideal MTF profile for all spatial frequencies was calculated and measured by this one edge technique for various pixel designs.

The advancement of the modern imaging system such as focal plane arrays (FPA), however, makes the conventional MTF measurement technique difficult due to the difficulty in separating the optical system response from that of the electrical device under test.^{4,6} Since the FPA does not fulfill the condition of isoplanatism, the MTF is not the true representation (Fourier transformation) of the line spread function in the electro-optical imaging sensor response. A variety of new test methodology, including time-delayed integration⁵ and the volume interference grating (holographic test pattern),⁶ has been introduced for the correction of the simple MTF technique for up to 6.8 μm pixel charge coupled devices.

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A new MTF standard should be established when the MTF is applied to discretely sampled, staring array systems. This technique is particularly attractive when the imagers are dealing with high-cost predesign and production control at a research and development level for the theoretical assessment of the electro-optical systems. The minimum resolvable temperature difference (MRTD) can be calculated with the modeling equation using MTF as one of the device parameters.

A knife-edge instead of the slit target is used for MTF instrumentation. Its advantage is that the slit-width correction can be excluded during the process. Therefore, increased accuracy is possible. In any case, the resolution of the spatial frequency will be independent of the focal length of the collimator of the optical system for the evaluation of the pixel MTF, and the edge itself is much simpler to manufacture than a narrow slit. Park et al. suggested averaging over an ensemble of point sources to account for the local shift variance.⁷ In another trial, random targets of known spatial frequency content were used, therefore eliminating position dependencies on the array. Recently Tzannes et al used a modified knife-edge technique to generate an edge spread function with a very high resolution.² A minimum of one pixel shift in edge location is needed over all scans to achieve the desired uniform edge distribution.

In this paper, a preliminary result of the pixel Modulation Transfer Function characterization for the optical and thermal imagers is discussed with contemporary software. The MTF will be measured experimentally by the modified single-edge technique using the MEALS system. Different sensor designs in sensor geometry will be evaluated with respect to fixed optical and electrical setups. Understanding the tradeoff between different figures of merit will enable us to achieve better designs in the future.

2. TECHNICAL BACKGROUND

Traditionally, the MTF was measured on devices that form continuous images using the response of the system to a known input, such as a point. Alternatively, a line source was imaged to arrive at the line spread function (LSF), which can be used to estimate a 1-dimensional profile of the 2-dimensional MTF. The knife-edge method, measures the edge spread function (ESF), the response of the camera to an edge. The ESF can then be differentiated to obtain an LSF. Difficulties arise when applying these methods to digital devices, however, because the discrete sampling of the focal plane causes the system to be locally shift variant. Therefore, the mentioned methods must be modified in order to be applied to sampled devices. Another approach is to utilize random targets of known spatial frequency content, which therefore eliminates position dependencies on the array.

In this work, in order to arrive at an MTF estimate, we used a modified knife-edge technique that generates an ESF with a very high resolution, by adjusting several scans across the knife edge to align with the desired direction.² The location of the edge is therefore shifted very slightly from one scan line across the edge to the next, which effectively increases the sampling by the number of superimposed lines shown in Figure 1. To avoid amplifying the noise during the differentiation of the ESF, we fit an analytic function to the ESF. The magnitude of the discrete Fourier transform (DFT) of the LSF is a profile through the center of the system MTF, in the direction perpendicular to the original knife edge. A major advantage of this method is that only a single image containing a rising or falling edge is needed to perform the measurement in each direction. An estimate of the MTF profile for all spatial frequencies can be derived from this one image. In addition, an elaborate target is not required, because any simple bar pattern or uniform straight edge is sufficient. The computations involved in the processing of the image data are straightforward and require very little processing time.

The optical transfer function (OTF) of an optical system is generally represented in a two-dimensional quantity as $F(v,w)$, where v and w are spatial frequencies. If the system is linear, isoplanatic, and incoherently illuminated, then the OTF is the inverse Fourier-transform of the point spread function (PSF), with x and y as the coordinates.⁴

$$F(v,w) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y) \exp\{2\pi i(vx+wy)\} dx dy \quad (1)$$

Mathematically, an extended object can be described as a superposition of an infinite number of periodic spatial components with frequencies from zero to infinity,

$$G(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(v,w) \exp\{-2\pi i(vx+wy)\} dv dw \quad (2)$$

Similarly, its image can be written as

$$G'(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g'(v,w) \exp\{-2\pi i(vx+wy)\} dv dw \quad (3)$$

where $g(v,w)$ are the spatial frequencies of test object bars. $g'(v,w)$ are their images.

In reference to the convolution terminology, this is to say: G' is the convolution of G and F and g' is the product of g and f , then we have the image forming theory expressed in two ways:

$$f(x,y) = |K(x,y)|^2 = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(v,w) \exp\{2\pi i(vx+wy)\} dv dw \quad (4)$$

and

$$G'(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |K(x-x_0, y-y_0)|^2 G(x_0, y_0) dx_0 dy_0 \quad (5)$$

where

K is the amplitude point spread function at (x, y) due to the disturbance at (x_0, y_0) ,
 G' means the product factor of the contrast of a grating, and the exponential term indicates the lateral shift of the image of the grating in comparison to the ideal image.

In fact, the OTF comprises two functions as follows:

$$(OTF) = (MTF) \exp\{i(PTF)\}. \quad (6)$$

The phase transfer function (PTF) gives mostly the calibration information. Therefore, the MTF is often used interchangeably with OTF and is the main concern for many cases in this study. Obviously, the MTF can be defined as g/g' .

MTF is in principle classified into three categories: scanning method, autocorrelation, and crossrelation methods. Of these, the scanning method seems to be most commonly used in many fields, and the line spread functions (LSF) measurement is equally preferable due to the fact that it can be obtained with a simple slit, and it is measure of fundamental definition. In general, the ideal system MTF is given by the product of the diffraction limited MTF of the optics and the ideal MTF of the pixel as:

$$MTF_{system} = MTF_{optics} \times MTF_{pixel} \times MTF_{electronic} \quad (7)$$

For a circular aperture, the diffraction-limited MTF of the optics is circularly symmetric. Its 1-D profile is given by⁶

$$MTF = \pi/2 [\cos^{-1}(f/f_c) - (f/f_c) (1 - (f/f_c)^2)^{1/2}] \quad (8)$$

for all $f_c \geq f$ and zero otherwise. The cutoff frequency f_c is related to the mean wavelength λ and f number of the optics, denoted $f/\#$, by the equation

$$f_c = 1/\lambda f/\# \quad (9)$$

The ideal pixel MTF, which is simply the magnitude of the Fourier transform of a rectangular function of width W (the width or height of the active area of the pixel), is given by

$$MTF_{pixel}(f) = |\sin(\pi f W) / (\pi f W)| \quad (10)$$

This ideal pixel MTF assumes a uniform response across the pixel (a perfect rectangular response), which is not necessarily the case. Therefore, we do not expect the measured MTF to display the minima present in the ideal MTF. Because the pixel MTF is fill factor dependent, the ideal system MTF in the horizontal and vertical directions can be different.

3. EXPERIMENTAL

An APS test sensor array has been designed and fabricated where different pixel shapes were placed. Research on analyzing the MTF for the general design of pixel shape is currently in progress. Explicit formulas for the modulation transfer function for the circle and for the rectangular have been derived. With this sensor, comparison can be made of the different fill factors (sensor geometry) for the same pixel size. A test bed for measuring MTF will give us a more complete understanding of the tradeoffs presented by the different pixel design geometry. Therefore, testing the pixel shape impact on the MTF is an important issue.

A single image of the APS array containing a slightly skewed horizontal or vertical edge is obtained. The scan line across the edge, a subpixel estimate of the location of the edge is computed. This is accomplished by first calculating an intensity midpoint for each scan line, which is simply the mean between the average intensity at the bottom of the step and the average intensity at the top of the step. A linear interpolation between the location of the two pixels along the scan line that straddle the intensity midpoint is performed, leading to an estimate of the edge location. Using linear regression, a straight line is fit through the edge location by fitting a function to the ESF. A Fermi function was used to achieve the desired fit. As published elsewhere,² the LSF was obtained by differentiating the ESF with respect to the scan direction.

A simple testbed setup for the MTF characterization, as shown in Figure 1, is achieved by modifying the laser scanner for finer steps. A sharp, single-edge response function was collected by the newly developed microelectronic advanced laser scanners with finer resolution (< one micron). The scanner equipped with blackbody source, Helium-Neon and Argon Ion probe lasers, mechanical choppers, and personal computer controlled spectrometer is located at the infrared imager system development lab.

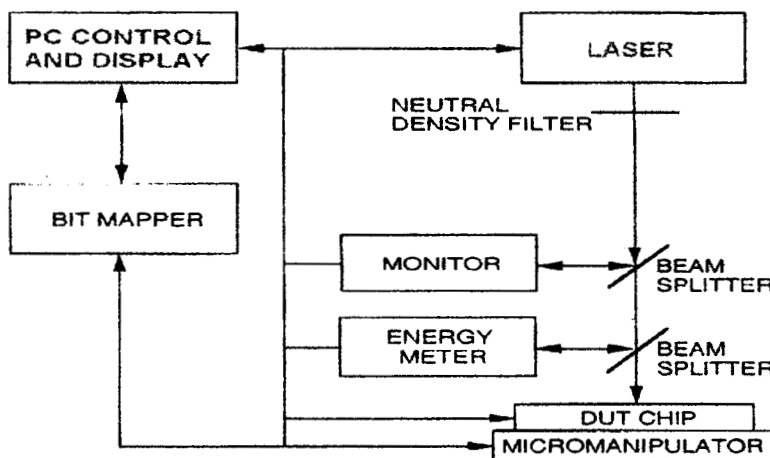


Figure 1. Block diagram of the Microelectronic Advanced Laser Scanner.

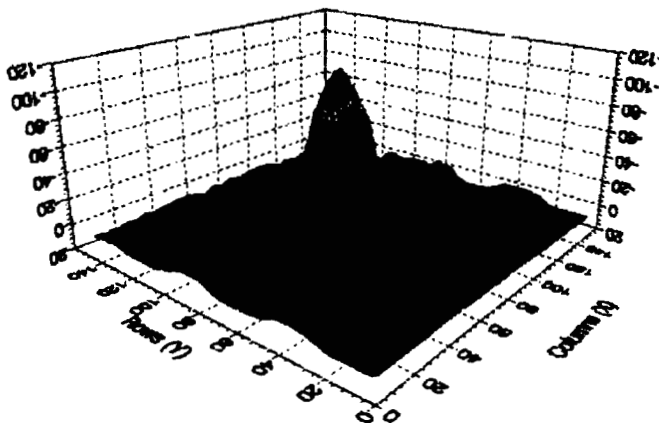


Figure 2. Typical crosstalk among the eight nearest neighbor pixels is 5.1%.

Crosstalk between two neighboring elements in a Focal Plane Array (FPA) occurs when signal incident on one element in the array is seen on another. This undesired effect can occur due to both the electrical and optical properties of the FPA. A single detector in an array is illuminated using a laser source coupled with a beam expander, collimating lens, and focusing lens. The crosstalk, the relative response of FPA to that of its neighboring arrays, was also measured as shown in Figure 2.

The various components of the MTF were discussed with respect to the crosstalk for implementing the true object image. All the measurements were performed using the same 2-mm/0.91 lens. By slowly turning the focusing ring on the lens while recording, we obtained a set of frames in which the bars pass through focus. Each one of these frames was then processed using the proposed algorithm. The final Fourier transformation of the smooth step response function was performed to find the modulation transfer function by the existing a desktop personal computer in an office space. In Fig. 3 we see a plot of the fits to the ESFs obtained from three of these frames, for a horizontal edge.

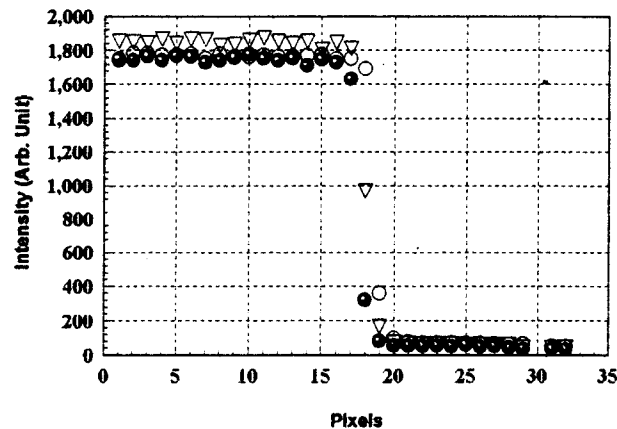


Figure 3. Edge Spread Function slightly adjusted to the edge that obtained from three frames of horizontal scans.

The active pixel test sensor arrays for the star tracker were already fabricated through the multioxide semiconductor implementation information services. Two different designs of pixel geometry of the active pixel test sensor were for the collection of the response signals. Necessary facilities and characterization equipment prior to carrying out this work for the electrical noise are available at JPL imager technology research and development lab. The instrumentation for material preparation and fabrication of sensors at the infrared imager system development lab include a temperature controllable mini refrigerator system (MMR Model K2205), HP4145 semiconductor parameter analyzer, Multipurpose Electrometer (Keithley Model 617), polarizing microscope, fabrication and thin-film deposition equipment, Magna IR Spectrometer 750 from Nicolet with pantium personal computers, PI-5800A Data Generator, PI-40001 Control Mainframe, and PI-40003 DC Power Mainframe from Pulse Instruments.

4. RESULTS AND DISCUSSIONS

Figure 4 shows the preliminary results of an active pixel focal plane test structure arrays image response. The fill factor is approximately 54% in the horizontal direction. The center-to-center spacing of the detectors for this array is $12.7 \mu\text{m}$ in both the horizontal and vertical directions. Using a lens system of 2-mm focal length and 0.91 $f/\#$, we performed the proposed knife-edge MTF measurement. The ESF for the horizontal direction scan image were obtained from the pixels in the outlined areas of the image shown in Fig. 6. Figure 5 shows the preliminary results of an active pixel focal plane test structure arrays image response in vertical direction. The fill factor is approximately 22% in the vertical.

This ideal pixel MTF assumes a uniform response across the pixel (a perfect rectangular response), which is not necessarily the case. Therefore, we do not expect the measured MTF to display the minimum present in the ideal MTF. Because the pixel MTF is fill factor dependent, the ideal system MTF in the horizontal direction can be different. The diffraction-limited optical MTF, the pixel MTF, and their product (calculated) are also plotted in Figures 4 and 5, assuming other MTF such as $\text{MTF}_{\text{electrical}}$ is constant throughout this measurement. Note that the measured MTFs are lower throughout the low frequency

rages than the calculated ideal MTFs, especially for the low vertical fill factor pixel, while the measured MTFs are higher at the high frequency ranges than those of the ideal MTFs. The latter may be due to the crosstalks between the neighbor pixels or diode leakage.

Because the pixel MTF is fill factor dependent, the ideal system MTF in the horizontal and vertical directions are different. A total fill factor of 12% was found for this example. However, because the MTFs in these two directions were not the same, the system MTF is non-symmetric. Therefore, we may reach a general conclusion about the actual shape of the 2-dimensional MTF by combining those results of two horizontal and vertical directions, respectively.

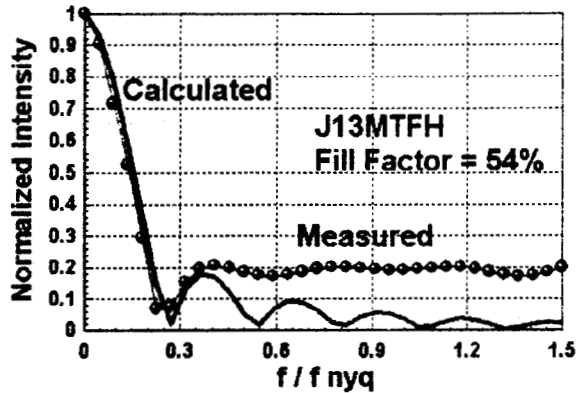


Figure 4. Calculated ideal pixel and measured MTF for the pixel size of $12.7 \mu\text{m}$ using a laser (λ of $0.63 \mu\text{m}$) and a 2-mm $f/0.91$ lens. The fill factor of the pixel in horizontal direction is 54%.

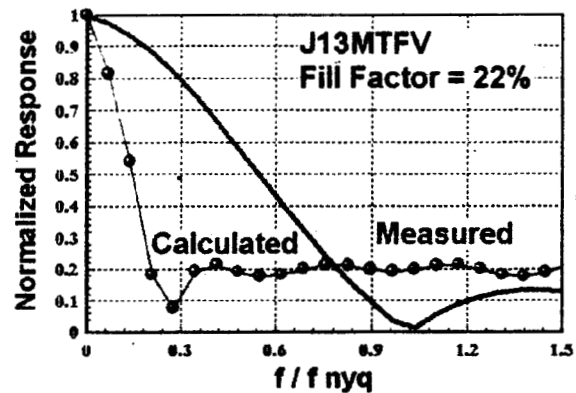


Figure 5. Calculated ideal pixel and measured MTF for the pixel size of $12.7 \mu\text{m}$ using a laser (λ of $0.63 \mu\text{m}$) and a 2-mm $f/0.91$ lens. The fill factor of the pixel in vertical direction is 22%.

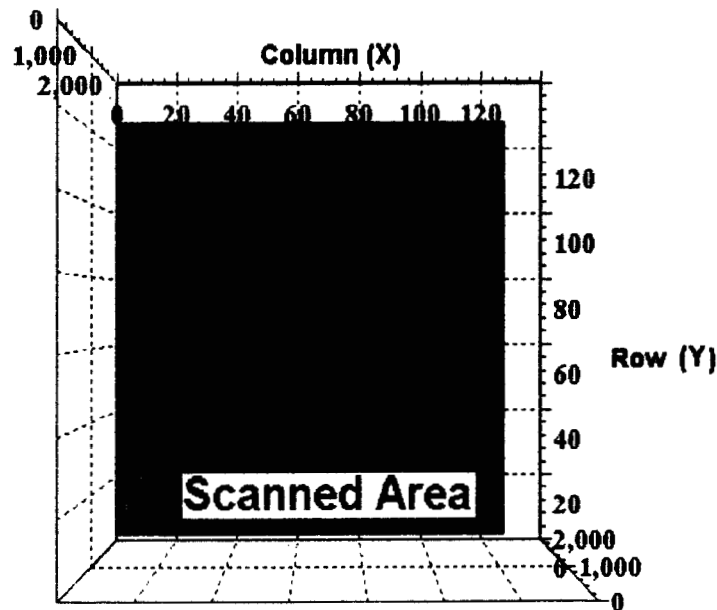


Figure 6. Active test pixel arrays used for the MTF measurements shown in Figures 4 and 5.

Figure 7 shows similar results of image responses of an active pixel focal plane test structure array. The fill factor is approximately 78% in the horizontal direction. The center-to-center spacing of the detectors for this array is also 12.7 μm in both the horizontal and vertical direction. The ESF for the horizontal direction scan image were obtained from the pixels in the outlined areas of the image shown in Fig. 9. The diffraction-limited MTF, the pixel MTF, and their product are plotted in Fig. 8. The fill factor is approximately 35% in the vertical.

The larger difference discrepancy between the calculated and measured MTFs that can be observed in Figures 7 and 8 than Figure 4 and 5 was due to the few data points to define the edge spread functions. The diffraction-limited MTF, the pixel MTF, and their product are plotted in Fig. 4, 5, 7, and 8 for a system with pixel size 12.7 μm , a λ of 0.63 μm , and a 2-mm $f/0.91$ lens. The frequency axis is normalized to the Nyquist frequency of the system, given by

$$f_{\text{Nyquist}} = \ell / 2d \text{ c/mrad.} \quad (11)$$

where ℓ is the focal length of the optics and d is the center to center spacing of the detectors. On all the MTF plots shown in Sec. 4, the measured MTF is plotted with the ideal pixel MTF, and the frequency axis has been normalized to f_{Nyquist} value of 0.08.

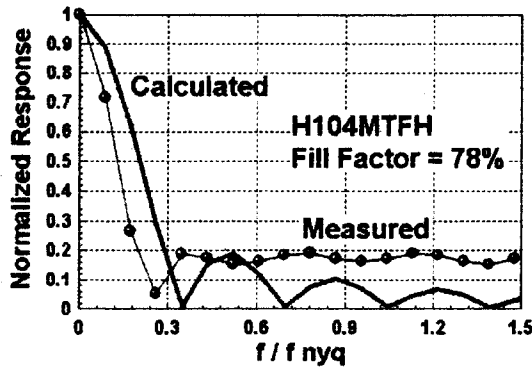


Figure 7. Calculated ideal pixel and measured MTF for the pixel size of 12.7 μm using a laser (λ of 0.63 μm) and a 2-mm $f/0.91$ lens. The fill factor of the pixel in horizontal direction is 78%.

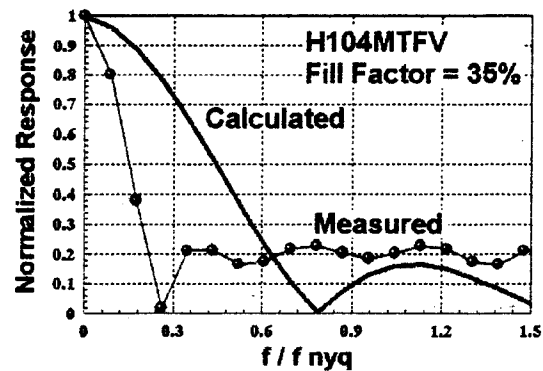


Figure 8. Calculated ideal pixel and measured MTF for the pixel size of 12.7 μm using a laser (λ of 0.63 μm) and a 2-mm $f/0.91$ lens. The fill factor of the pixel in vertical direction is 35%.

For the higher frequency ranges, no effect of the cascaded Charge Transfer Efficiency (CTE) is evident in either direction. This is expected due to the single potential charge transfer design of the active pixel readout circuits. The difference in MTFs generated in both directions in different ranges shown in Figures 4 and 7 must be due to the crosstalk between two neighboring pixels as shown in Figure 2.

5. SUMMARY

The performance of active pixel focal plane arrays is characterized by estimating their spatial frequency responses. A modified knife-edge technique that estimates 1-dimensional system MTF profiles is used. Advantages of the technique include the need for only a single image to perform the measurement in each direction and the fact that moving parts and high-precision alignment are not necessary. Various silicon active pixel sensor array responses that are not affected by the charge transfer efficiency (CTE) were measured and compared with calculated MTF profiles in both the horizontal and vertical directions. Calculated ideal pixel MTF of the different fill factor was compared with measured MTF and overall image quality. Furthermore, it was demonstrated that the technique can be utilized as an timely evaluation technique of the focal plane array pixel design.

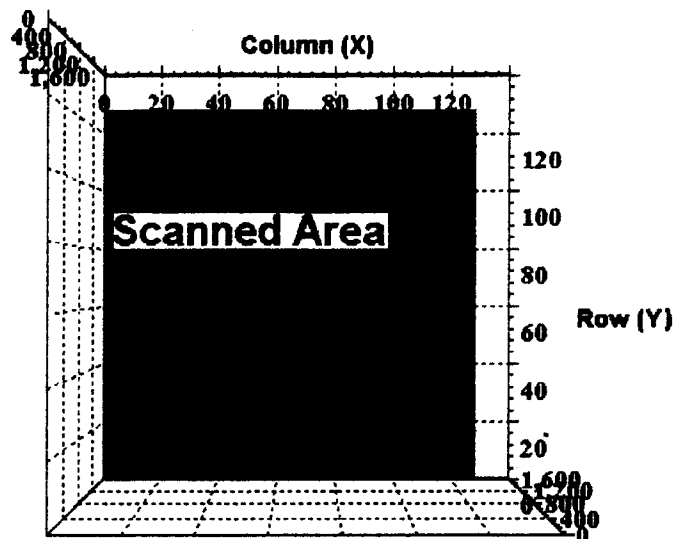


Figure 9. Active test pixel arrays used for the MTF measurements shown in Figures 7 and 8.

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